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SYMPOSIUM.

THE MODERN THEORY OF ELECTRICITY AND MATTER.

I.

THE GENERAL PRINCIPLES.

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The field of the present discussion is so large and the time for it is so limited that I feel sure I can serve you best by foregoing the luxury of an historical introduction and by entering somewhat abruptly into the heart of the subject before us. I wish, then, to discuss before you the general ideas and beliefs respecting the ultimate nature and relations of matter and electricity which are in the foreground at the present time.

In dealing with progress of scientific explanation it is necessary to remember, what we too often forget, that the verb "to explain," when applied to a new complex phenomenon, means merely the expressing of it in terms of something else either more *familiar* or more *fundamental*. An exaggerated example of the first type is furnished by all the old anthropomorphic explanations of natural

phenomena in which the less familiar actions of the outside world were expressed in terms of the intimate and much more familiar workings of the human mind. "Nature abhors a vacuum," and like expressions, show the type.

The progress of science exhibits countless examples of the second type of explanation, for, wherever two or more concepts are merged into a profounder synthesis, there we have an expression in terms of something more *fundamental.* When, for instance, it is said that the phenomena of tidal action are caused by the gravitational attraction of the moon, it is stated merely that this action is really one with countless other phenomena which, although dissimilar on the surface, merge with it into the profounder synthesis known as the law of gravitation.

It is important also to remember in this connection, that *in* this process of explanation we always have left the one concept into which the many have merged, so that as time goes on the alternatives of explanation grow fewer and fewer, and in the end—if we can imagine an end—there is no explanation, because there is no more fundamental fact.

You will pardon me, I am sure, if I say one word more with reference to this question of ultimate explanation.

We have all heard people say, "Isn't it wonderful that so much is known *about* electricity, and yet no one knows what electricity *is*!" Now, doubtless the observation has some meaning, but certainly not as much as it seems to have; for, after all, what do they mean by "what electricity is"? Do they expect the announcement some day that electricity is a liquid similar to water, or a gas similar to air?

It is becoming more and more probable that electricity is the chief constituent of the atoms themselves, and an electron, which is a particle of electricity, if anything is, is certainly less than a ten-thousandth the size of one of the atoms in a water molecule. Therefore after the *"is,"* following the word "electricity," there is nothing to put which is already familiar, and when the profounder concept does come, it will be extremely fundamental, but it will cause the layman no thrill of long-anticipated disclosure.

A special type of critical attitude is necessary in dealing with

fundamental physical concepts and it is an attitude which we seldom assume, so that these remarks have been necessary to introduce properly the three fundamental realities which modern physical theory now contemplates, namely: the *atom*, the *electron*, and that mysterious but perhaps even more fundamental entity known as *energy*.

A few years ago I would have mentioned also the *ether*, but I am a little reluctant to do so now. Not that there has been a sudden revolution in the realm of thought, resulting in the complete overthrow of the old regime, but rather that development has been such as to render the concept of an ether less and less impressive—one might say—and less and less important. Changes of opinion in such matters are, it seems to me, partly questions of emphasis, and radiant energy in all its nakedness is now usurping much that the ether has long stood for.

Of course, the loss, or rather the dimness, of the ether concept implies a certain loss of concreteness; but, as has been said, concreteness in new concepts, founded as it is on familiarity, is a secondary virtue and is of far less importance than the value of a concept in furthering the great process of induction which leads us to more and more general truths.

Although the concept of *the ether* is slowly dimming, the concept of *the atom* is becoming more and more definite and vivid. The study of the scintillations caused by radium rays and the work of Rutherford in counting the alpha particles give us, for the first time in the history of physics, definite observable results which apparently can only be due to the action of single atoms, and which therefore furnish proof beyond reasonable doubt that the atom and molecule are names of actual realities, and are not merely two prominent words in the statement of a useful hypothesis.

The kinetic theory of matter, carrying with it the concept of temperature as violence of atomic vibration, has also been strengthened enormously by the work of Perrin and Einstein on the Brownian movement. They find that microscopic particles in solutions have a perpetual motion in close agreement with the kinetic theory. Indeed, they act in all ways like big molecules, obeying the kinetic laws deducible from mechanics. Their observable agitation is part

of the general vibratory motion which distinguishes a hot body from a cold one.

The electron, too, is now well within what we might call "the exclusive circle of the truly real." This minute charged body has by many researches, among them the recent one of Millikan, been shown to be a definite reality, present in all matter and entirely or largely responsible for all the phenomena we know as electrical.

The other fundamental entity, energy, is also, if I may be allowed the phrase, "mysteriously real." Radiant energy leaves the sun eight minutes before it reaches the earth, and must, therefore, exist during that time in the space between, dissociated from ordinary matter. When it finally strikes some object and is absorbed, it gives the object a thrust—that is, communicates momentum to it, as a bullet would do—and at the same time, of course, it increases the total energy of the body. In the same way, a body radiating energy recoils during the emission in a way similar to a gun.

All this is remarkably like the action of ordinary matter. We can, however, say even more. There is very good reason for believing that, were it possible to shut up a large amount of radiant energy in a hollow box, the inner surfaces of which were perfectly reflecting, so that the rays would be reflected back and forth indefinitely, we would find this confined energy to possess both mass and weight. Not many decades ago such an idea would have seemed absurd, but it is hard now to avoid the conclusion that such would be the case.

I can do no better now than to describe in a few words the picture which we have today of the ultimate structure of matter. A piece of matter is composed of particles called atoms, which, by uniting in groups in various ways, form the characteristic aggregates which we know as molecules. There are about one hundred different kinds of atoms, varying in relative weights from one to 240, and in relative volumes from one to about 16. The approximate diameter of an atom is one one-hundred-millionth of a centimeter.

These atoms are in ceaseless motion to and fro, the energy of this motion determining what we call the temperature of the body. Within the atoms and in the spaces between them are large numbers of very much smaller particles known as *electrons*. They each

carry a negative charge, which is relatively enormous, considering the fact that the approximate electronic diameter can scarcely be more than one one-hundred-thousandth that of the atom.

When any cause sets up a general movement of the electrons within a body, we have a current of electricity, while the random vibratory heat motion of atom and electron is the cause of continual emission of radiant energy to other objects or to outside space.

A piece of matter is thus a complex system composed of an inconceivably large number of ultimate units, atoms and electrons, in ceaseless motion to and fro, and permeating all is the mysterious, matter-like entity which we have called *radiant energy,* and which ever seeks to escape with an enormous, though perfectly definite, velocity into the space outside. Some of it succeeds in escaping, but there appears to be a vast amount which in some way is imprisoned in the atom-electron aggregate and thus never becomes "radiant" in the strict sense of the word, though it resembles radiant energy so closely as almost to warrant the same name.

Having thus obtained an impressionistic view of the structure of a piece of matter, I would like to call attention to the properties of the space surrounding an electron, or, what is the same thing for our present purpose, the space surrounding any body, say a small sphere, possessing an electric charge. This space is the seat of what we call electric force, and is known as an "electric field." Now, it is a well-known conclusion and one which cannot at present be in any way avoided, that the energy which the body possesses, by virtue of its charge, that is, the energy originally required to charge it, resides in the electric field around the body, and not on or in the body itself. The existence, without apparent motion, of this energy in what seems to be empty space is very remarkable, but the conclusion that it *is* there is unavoidable, and after all there is no great difference between the discarnate state of this energy and the state of the radiant energy of the sun on its way to the earth. From the older point of view this energy in the electric field was "strain energy" in the ether, the so-called strain being similar to what we would get in an immense block of rubber if a pin-head embedded at its center were to swell into the size of an egg. The rubber would be pushed back in all directions and the energy of this compression

would be stored up throughout the whole mass, a great deal of it near the center, but an appreciable amount even out at the very limits of the block. From the present point of view, we think more about the energy and less about the ether, but the general effect is the same.

Let us call this energy located in the space surrounding an electric charge "bound energy," to distinguish it from the closely similar type of self-propagating energy which can also exist in space and to which we apply the term "radiant," and let us then ask what properties, if any, this bound energy gives to the body which it surrounds.

I stated before that radiant energy, when it struck a body, communicated momentum to it in the same general way as a material body, say a flying bullet, would do. The radiant energy thus acts as if it had mass, and the question now is, "May the 'bound energy' surrounding our charged sphere also be considered to possess mass?" We may answer this question *in the affirmative,* for this bound energy is electric energy, and, thanks to the great founders of electrical science, we know the laws of electric action pretty completely.

Applying these well-known laws we find that when our charged sphere is moved, it acts like a current of elecricity and sets up a magnetic field about it, and the formation of this field acts, by the well-known laws of induction, to retard the motion of the charge. Thus the setting in motion of the sphere is made more difficult by reason of its charge, an effect which is equivalent to saying that the sphere has added mass.

If this were all, we might say that the added *charge* of electricity had mass, so that the mass increment is on the surface of the sphere where the charge is known to reside. This is *not* all, however, for by letting the sphere expand we can decrease the energy in the space about it without changing the magnitude of its charge; and we find, by further simple application of well-known electrical laws, that the new mass will change *exactly as the energy changes.* If the new mass had been proportional to the charge, it would remain constant with it instead of changing with the energy. Thus what is known as the electromagnetic mass of the sphere is

proportional to its energy. I was able to show, several years ago, that, with certain limitations, this same result is true for any electric system.

It may be said, then, to follow from what might be called elementary electromagnetic principles, that the electromagnetic mass of an electric system is proportional to its electric energy. Now Hasenhorl, at Plancks's suggestion, I believe, had already shown that a similar result applied to radiant energy properly speaking; for he found that from known laws of radiation it followed that a hollow box, like that mentioned earlier, with perfectly reflecting walls, would, when filled with radiant energy, act as if it had added mass. That is, the pressure of radiation would be so changed by the increasing velocity of the box as to oppose the force causing this increase, and this inertia, this added mass, he found would be proportional to the amount of energy present. My proportionality constant agrees with his. Lewis, from a totally different point of view, has reached a similar conclusion.

It is, as you know, one of the profoundest generalizations in modern physics that light and other forms of radiant energy are in reality all forms of electromagnetic energy. Hasenhorl's results, therefore, that confined radiant energy possesses mass, combined with the result obtained in connection with the bound energy surrounding electric charges, *gives us the general result that all electromagnetic energy, whether bound or radiant, possesses mass,* and this mass is proportional to the quantity of energy present.

You see that the concept of energy, although in some ways very illusive, is getting singularly definite and persistent. Since we see that electric mass is proportional to electric energy, the question naturally arises: How much of the mass of the electron is due to the electric energy surrounding its relatively enormous charge, and how much is the "ordinary mechanical mass" of its body proper? We have a means of distinguishing between the two masses, for the electric mass does not remain constant when the velocity of the charge becomes great. Electrical laws tell us that it *increases,* very slowly at first, then more rapidly, and that as the velocity of light is approached it becomes very great. Of course, in ordinary me-

chanics, on the other hand, the mass of a body is considered to be a constant and to have nothing whatever to do with the velocity.

By studying experimentally the deflection of the beta-rays of radium, which consist of streams of electrons travelling at velocities very near that of light, Kaufmann has shown that the experimental change in mass fits the mathematically deduced change when, and only when, the "ordinary mechanical mass" is negligible. In other words, as near as measurement can yet go, the mass of the electron is *entirely* the electromagnetic mass of the surrounding energy, and it has no appreciable mass of what I might call "the old-fashioned mechanical kind."

This is a result of extraordinary importance in physical theory, for it immediately suggests the general question, "Is all mass of this origin?" Since an ordinary piece of matter is permeated with electrons and also with the radiant energy which all parts of it are constantly absorbing and emitting, it is an absolutely unavoidable conclusion that at least part of the total mass is of this electromagnetic type. But the question is, "Is *all* mass electromagnetic?" or, more properly speaking, *"Is all mass of the same type, and does it all depend upon the velocity in this same way?"* An affirmative answer would imply a profounder unity in physical phenomena than has hitherto been recognized and would thus correspond to the passage to a deeper synthesis. Of course, the deeper concept which unites two or more others should, in strictness, be made independent of these others; but, although definitely foreshadowed in the present case, the detailed statement of this deeper law is at present impossible *except as regards changes due to motion;* so that this, taken with the fact that electromagnetic phenomena are so familiar that we may be said to know their *modus operandi* in terms of magnetic fields, electric forces, and the like, renders it provisionally allowable to state the question in the form: "Are the laws of electricity and optics the laws of matter in general?"

We have, during the last few years, been attaining with greater and greater surety a definite answer to this question. It has come through the gradual adoption of a remarkable concept, profound in its meaning and very far-reaching in its consequences. I refer to the so-called "Principle of Relativity."

There are times in the history of science when various contradictions require that the process of building stop until the most fundamental concepts are reëxamined. This was true in the history of astronomy at the time of Copernicus. The prevailing conception of the earth as a fixed center about which all the other bodies revolve had been practically sufficient for a long time, but gradually difficulty after difficulty arose until it was no longer possible to patch up the old theory to meet the accumulation of stubborn facts. Only by a change in the most fundamental conception, namely, that of the earth as a fixed center, could harmony be brought out of chaos and a new period of development commenced. We seem to be passing through a somewhat similar period in physics, and the "Principle of Relativity" contains the modified concepts.

By way of transition, let me make one or two statements at this point about electric and magnetic systems in general. It can readily be shown to follow from known electromagnetic laws that two electric charges of the same sign moving side by side with the same velocity repel each other *less* than when the two are stationary. This is due largely to the fact that, when moving, each charge is surrounded by a magnetic field and this magnetic field introduces new forces.

This simple statement introduces a far more general one, for it may be shown that a steady motion of *any* electromagnetic system so changes the force between the various parts of the system that it tends to take up a new position of equilibrium. *The forces are such that the whole system tends to contract along the line of motion.* If it be allowed so to contract until it reaches this new position of equilibrium, then everything will be as before the system was set in motion, with two important exceptions, if the system has any internal motions caused by electromagnetic force. First, two motions, say the oscillation of two charges, one in the front of the system and the other behind, which in a stationary system take place simultaneously, will, in the moving system, take place not quite simultaneously; for the forward one will be somewhat behind in time; and, second, all such motions will take place a little slower than they did in the stationary system. The term electromagnetic

system, used in this sense, includes, of course, all radiant energy, for it will be remembered that this type of energy is also electromagnetic.

Thus, on grounds of well-established electromagnetic theory and without any new fundamental conceptions whatever, we can make a general statement that *any electromagnetic system, when set in motion, tends to assume a new state of equilibrium, and if this change be allowed to take place, then all effects, electric and optical, take place in the changed system in a manner exactly corresponding to the way they did take place before the system was set in motion.*

A moment's thought will make it evident that we are here apparently in the presence of a fundamental lack of harmony between electromagnetic phenomena and the phenomena connected with matter in general; for, from the ordinary point of view, the parts of a "rigid body" maintain their mutual relations unaltered whether or not it is set in motion, while, as we have seen, this is not true of electromagnetic systems.

Now, we have no choice but to consider a *real* body as a combination made up of the two kinds of systems if there are two, the electromagnetic type and the "rigid body" type; hence it is clear that, when such a mixed system is set in motion, there will be a considerable amount of what we might term internal discord, owing to the conflicting tendency of the two types. It would be very easy to distinguish such a mixed moving system from the same system at rest, because its parts would bear quite different relations to each other than they did before. Setting a real system in motion would be like heating an object made up of two substances having different coefficients of expansion. The parts of such a system would then bear totally different relations to each other than when the whole thing was at rest, and the internal dissension would increase with the velocity and would depend on its direction.

Now as a matter of fact, we all live on such a moving mixed system, a system which is going around the sun with a velocity of nearly twenty miles a second; and yet, although many carefully planned and executed experiments have been carried out to detect differences in the actions of various electrical and optical systems, according as they are made to face with the earth's velocity or

across it, every one of them has given negative results, and has thus shown that the relative parts of the system *bear the same relation to each other, no matter what the direction of motion is.*

It is like finding that an object made up of metal and glass had no strains set up in it when heated, a result which could only be attained if the metal and glass had the same coefficient of expansion.

What are we to conclude in the case before us? There seems to be no alternative. We already have seen that electrons are among the fundamental constituents of all atoms; we have seen that radiant energy is electromagnetic and that such energy permeates all matter. We have seen that energy resembles matter in possessing mass, and that, therefore, to the same degree, matter resembles energy. The necessary conclusion seems to be that *all physical phenomena obey the same general laws of which the known electromagnetic laws are as yet the completest expression.*

And now to what have we committed ourselves by this conclusion as regards changes due to motion? Merely this: that all real systems being ultimately "electromagnetic" in the above sense, undergo certain changes when set in motion, but these changes are such as to leave all parts bearing the same relation to each other. Thus since the knowledge of an observer travelling with the system is only relative, he is not able to detect such absolute changes, just as we are not able to detect the motion of the earth. The changes in his system would be noticeable to an observer whose instruments did not move, but cannot be detected by moving instruments.

The kind of change which we have said is produced in a system by setting it in motion has one property which is important and profoundly significant. It is that the moving observer sees precisely the same change in stationary systems which he is passing as the stationary observer sees in the moving system; so that not only can the moving observer not detect his motion by means of his instruments, but *the two observers together,* if their memory fail, can by no means tell which is moving. There is, in other words, a very complete symmetry with regard to what the two observers can actually find out about their systems, although we called one of them stationary in the beginning.

Because of this complete symmetry the most conservative among

us will admit that the concept of absolute motion *need not be used very often*, at least, in the science of the future; if the foregoing views are true ones. The modern group of conceptions known as the "Principle of Relativity" teaches that the idea of absolute motion is entirely superfluous, and that the time honored concepts of space and time, as independent of all motions, do not accurately fit the real universe and should be modified.

Modified in what way? Real time is measured by real clocks and real distance is measured by real rigid bodies, and we find an unexpected discord between moving clocks and stationary clocks, and between moving rods and stationary ones. We have, therefore, no possible use for what might be called "universal time." We might form a vague concept of a "cosmic second" pervading the universe, but we could do nothing with it, and it would therefore be entirely artificial. Whenever we wished to think about an actual moving object and wished to measure some vibration frequency on it, let us say, we would have to use some actual clock-beat or other periodic phenomenon as a unit. So that the actual universe has us hopelessly in its grasp, and our concepts of space and time to be valuable must be in harmony with the habits of real things.

The principle of relativity, therefore, makes changes in the fundamental concepts of space and time for moving systems; the second in a moving system is longer, the meter, in the direction of motion, shorter, than in stationary systems. The units then are in harmony with real happenings in such systems, and this makes it possible to introduce the last great synthesis of modern theory, the deeper unity of physical law under the dominance of what we have known as electromagnetic principles; and this brings us one step nearer to the last, ultimate generalization which is the unattainable ideal of science.

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